NISTIR 5341

Assessment of Uncertainties of Liquid-in-Glass Thermometer Calibrations at the National Institute of Standards and Technology

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1. Introduction

A new policy for expressing uncertainties of calibration results was adopted at the National Institute of Standards and Technology (NIST) in October 1992 [1]. The method chosen is essentially the one recommended by the International Committee of Weights and Measures (CIPM) in 1981. A detailed description appears in the "Guide to the Expression of Uncertainty in Measurement" [2], and was prepared by individuals from the Bureau International des Poids et Mesures (BIPM), the International Electrotechnical Commission (IEC), the International Federation of Clinical Chemistry (IFCC), the International Organization for Standardization (ISO), the International Union of Pure and Applied Chemistry (IUPAC), the International Union of Pure and Applied Physics (IUPAP),and the International Organization of Legal Metrology (OIML). It was published in October 1993 by the ISO. The new system will be implemented at NIST by January 1, 1994.

The following sections explain how each component of the combined standard uncertainty was determined and how the combined standard uncertainty was calculated for each type of liquid-in-glass thermometer for which data were available.

2. Calibration Procedure

Before liquid-in-glass thermometers are calibrated, they are examined under a microscope. Any thermometer with a defect, such as foreign material (piece of glass) in the capillary, is ineligible for calibration. All gas is removed from the bulb and all of the mercury is united.

Acceptable liquid-in-glass thermometers are then calibrated [3], starting from the lowest calibration points and proceeding to the highest calibration points requested. In most cases the lowest calibration point is the ice point (0 °C). This is considered a "fixed point" in liquid-in-glass thermometry, since a properly prepared ice bath requires no standard thermometer to determine its temperature. It is considered to have a temperature of 0.000 °C within +0/-0.005 °C. If calibrations at temperatures below the ice

point are requested, they are done before the ice point measurement.

The thermometers are then placed in a constant-temperature, stirred-liquid bath, or a series of stirred baths, along with a standard platinum resistance thermometer (SPRT) that has been calibrated on the International Temperature Scale of 1990 (ITS-90) [4] by the NIST Platinum Resistance Thermometer Calibration Laboratory. All calibrations in the Liquid-in-Glass Thermometer Calibration Laboratory are on the ITS-90 Scale. The SPRT is read three times and the liquid-in-glass thermometers are read twice at each calibration point. At each calibration point, the temperature of the bath is calculated from the average of the three resistance values, and an average of the two readings for each of the liquid-in-glass thermometers at each calibration point is determined. The difference between the bath temperature and the average reading of a thermometer is the reported correction for that thermometer.

3. Uncertainty

The combined standard uncertainty (u_c) that is required for liquid-in-glass thermometers calibrated at NIST is the square root of the sum-of-the-squares of the Type A (u_i) and Type B (u_j) standard uncertainties. The Type A standard uncertainty is the pooled standard deviation over the temperature range of thermometers where data are available. The Type B standard uncertainty is determined from uncertainties due to the equipment used in the calibration process. A coverage factor of $k=2$ is used to calculate the expanded uncertainty, $U=ku_c$.

3.1. Type A Evaluation of Standard Uncertainty

3.1.1. Use of Check Standard Thermometers

Liquid-in-glass thermometer check standards belonging to NIST are incorporated into the calibration process described above. These liquid-in-glass thermometers are calibrated at the same calibration points that are requested by the customers for their thermometers. The check standards are calibrated as if they were submitted for test by an outside company. The computed corrections on the check standards are compared with the corrections obtained from previous calibrations. If the corrections for a given check standard agrees to within the uncertainty specified for that type of thermometer, it can be assumed that the calibration system was performing well and that the calibration of the other thermometers is acceptable.

The use of check standards was initiated to ensure that the calibration process was being performed properly. However, after many years, a large database has been generated which can be analyzed to establish uncertainty values for some liquid-in-glass thermometers. The corrections obtained from repeated calibration

TABLE 1

TYPICAL CORRECTIONS AT VARIOUS TEMPERATURES FOR TOTAL IMMERSION CHECK STANDARD THERMOMETER, SERIAL NUMBER 274762

DATE	3/26/76	3/29/76	4/1/76	4/6/76	4/21/76	5/17/76	5/25/76
BOOK	F115	C193	C193	C193	G30	C194	F115
PAGE	182-83	169	173	174-75	192-93	2	188
Temp. (°C)				Corrections (°C)			
0	+0.130	+0.130	+0.130	+0.129	+0.129	+0.125	+0.130
1							
2							
3							
4							
5							
6							
7							
8							
9							
10		+0.150	+0.153	+0.149		+0.157	+0.148
11							
12							
13							
14							
15							
16	+0.069						+0.070
17							
18							
19					+0.121		
20		+0.134	+0.127	+0.132		+0.131	
21	+0.121				+0.125		+0.127
22					+0.107		
23							
24					+0.095		+0.093
25					+0.103		
26							+0.098
27	+0.100				+0.108		
28					+0.123		
29							
30		+0.138	+0.136	+0.135	+0.134	+0.142	
31					+0.106		+0.108
32							+0.100
33					+0.095		
34					+0.074		
35							
36							
37							
38							
39							
40		+0.095	+0.102	+0.096		+0.100	
41							
42							
43							
44							
45							
46							
47							
48							
49							
50		+0.138	+0.136	+0.135		+0.136	

of the check standards are recorded in data books. A sample sheet of the data taken for thermometer with serial number 274762 is given in Table 1. This thermometer is for use at total immersion, has a range of -1 to +51 °C and is graduated in intervals of 0.1 °C. The uncertainty of this thermometer, which was published in September 1988 in NIST SP 250-23, Liquid-in-Glass Thermometer Calibration Service [3], and based on a limit to random error of three standard deviations plus the systematic error, was 0.03 °C.

Unfortunately, the check standards represent only a few of the many different types of liquid-in-glass thermometers. Data are being obtained at this time on almost all of the thermometers shown in the tables of uncertainty, which are given at the end of this report, and the results of these measurements will be published in the revised version of SP 250-23.

3.1.2. Calculation of the Type A Standard Uncertainty

Since 1990, all of the old, manually-controlled temperature baths used previously for the calibration of liquid-in-glass thermometers above 0 °C have been replaced. During this period of time, data that have been collected on the check standards represent an improvement due to the use of the new, more efficient, baths. Unfortunately, very few data have been collected to date and there are not enough to do a meaningful statistical analysis. The Type A standard uncertainty, therefore, was calculated from the data that were collected from approximately 1972 through 1982. During that time, 14 liquid-in-glass thermometers (total-immersion type with two thermometers for each of the seven temperature ranges of calibration), representing the most accurate types in a given temperature range, were used as check standards. Prior to the thermometers being used in a calibration, they were kept at room temperature (23 °C) for three days, thereby allowing the bulb to recover from its previous thermal cycling. Since no Celsius scale thermometers were available for the evaluation of low temperature calibration points, thermometers graduated in degrees Fahrenheit were used. All of the thermometers had an ice-point scale, either on the main scale or on an auxiliary scale. The range, graduation interval, and resolution of the check standard thermometers are given in Table 2.

Because the customer may request calibration at any given point, not every correction recorded for the check standards could be used in the analysis, since measurements were not at the same temperature. Most calibrations are performed at temperature intervals of 10, 20, or 30 degrees; therefore, the data taken at these intervals were used in the analysis. For each check standard, the correction versus temperature was plotted as a function of time over a period of five to twelve years. These plots are shown in Figures 29(a) to 42(a2) of NIST SP 250-23 [3]. Several of the plots show the effect of a permanent change in bulb volume with time (and use). As the volume of a liquid-in-glass

TABLE 2

SPECIFICATIONS OF THERMOMETERS USED AS CHECK STANDARDS

Temperature Range (°F)	Thermometer Graduation (°F)	Resolution (°F)
-60 to -30	0.2	0.01

Temperature Range (°C)	Thermometer Graduation (°C)	Resolution (°C)
0 to 50	0.1	0.005
50 to 100	0.1	0.005
0 to 100	0.2	0.01
100 to 200	0.2	0.01
200 to 300	0.5	0.05
300 to 500	1.0	0.05

thermometer bulb increases or decreases, the thermometer readings will decrease or increase, respectively, throughout the whole range. This accounts for the uniform shift of the correction versus temperature curves seen in some of the examples. In order to analyze the data accurately, an adjustment must be made for the bulb volume change. All of the data were adjusted for a constant ice-point temperature reading on a given check standard thermometer representing an approximate average of the ice-point corrections. The adjusted data for selected points were again plotted and the results were given in Figures 29(b) to 41(b) of NIST SP 250-23 [3].

The standard deviation of the check standard thermometers as computed for each nominal bath temperature is a measure of both the instability of the thermometer and the random error in realizing the bath temperature. The pooled standard deviation over the temperature range is taken as the Type A standard uncertainty for the calibration in that range (u_i). The results are given in Table 3, expressed as $2u_i$. The column titled "Degrees of Freedom" indicates one less then the number of measurements taken at the specified temperature.

TABLE 3

TYPE A EVALUATION OF STANDARD UNCERTAINTY
COMPUTED FROM CHECK STANDARD MEASUREMENTS

Temperature Range (°F)	Bath Temperature (°F)	Check Standard Number	Twice the Type A Standard Uncertainty ($2u_i$)	Degrees of Freedom
-60 to -30	-30	T531438	0.021	9
	-40	T531438	0.033	10
	-50	T531438	0.037	9
	-60	T531438	0.034	9
	-30	T531432	0.033	9
	-40	T531432	0.041	9
	-50	T531432	0.033	9
	-60	T531432	0.050	9
		Pooled	0.036	73

Temperature Range (°C)	Bath Temperature (°C)	Check Standard Number	Twice the Type A Standard Uncertainty ($2u_i$)	Degrees of Freedom
0 to 50	10	274762	0.009	50
	20	274762	0.013	66
	30	274762	0.011	62
	40	274762	0.013	55
	50	274762	0.013	57
	10	274764	0.010	50
	20	274764	0.011	67
	30	274764	0.010	64
	40	274764	0.010	58
	50	274764	0.014	58
		Pooled	0.011	587
50 to 100	60	4030424	0.013	33
	70	4030424	0.010	18
	80	4030424	0.013	29
	90	4030424	0.015	17
	100	4030424	0.019	37
	50	4030425	0.012	20
	60	4030425	0.012	37
	70	4030425	0.011	27
	80	4030425	0.013	33
	90	4030425	0.013	24
	100	4030425	0.020	43
		Pooled	0.015	318

Temperature Range (°C)	Bath Temperature (°C)	Check Standard Number	Type A Standard Uncertainty (2 Standard Deviation)	Degrees of Freedom
0 to 100	10	48425	0.020	22
	20	48425	0.021	44
	30	48425	0.024	38
	40	48425	0.017	42
	50	48425	0.019	40
	60	48425	0.017	32
	70	48425	0.013	17
	80	48425	0.021	30
	90	48425	0.022	19
	100	48425	0.023	29
	10	198694	0.019	30
	20	198694	0.017	49
	30	198694	0.016	52
	40	198694	0.020	43
	50	198694	0.017	55
	60	198694	0.018	31
	70	198694	0.021	23
	80	198694	0.017	37
	90	198694	0.024	27
	100	198694	0.016	40
		Pooled	0.019	700
100 to 200	100	382213	0.031	35
	110	382213	0.024	9
	120	382213	0.038	23
	130	382213	0.039	8
	140	382213	0.045	19
	150	382213	0.049	21
	160	382213	0.033	18
	170	382213	0.054	12
	180	382213	0.058	26
	190	382213	0.061	6
	200	382213	0.067	36
	100	382215	0.051	35
	110	382215	0.031	9
	120	382215	0.058	26
	130	382215	0.030	16
	140	382215	0.059	28
	150	382215	0.036	25
	160	382215	0.066	24
	170	382215	0.055	11
	180	382215	0.075	21
	190	382215	0.047	9
	200	382215	0.097	34
		Pooled	0.056	451

Temperature Range (°C)	Bath Temperature (°C)	Check Standard Number	Twice the Type A Standard Uncertainty ($2u_i$)	Degrees of Freedom
200 to 300	200	T112411	0.064	2
	210	T112411	0.104	3
	230	T112411	0.041	2
	250	T112411	0.045	13
	270	T112411	0.052	4
	300	T112411	0.048	14
	210	T112412	0.040	2
	240	T112412	0.020	2
	250	T112412	0.027	9
	260	T112412	0.056	5
	270	T112412	0.070	4
	290	T112412	0.072	2
	300	T112412	0.041	13
		Pooled	0.050	75
300 to 500	320	234453	0.204	3
	340	234453	0.135	3
	350	234453	0.166	8
	360	234453	0.204	2
	400	234453	0.034	3
		Pooled	0.160	19

3.2. Type B Evaluation of Standard Uncertainty

It is necessary to assess the Type B standard uncertainty, which in the case of liquid-in-glass thermometry arises essentially from the uncertainty due to the equipment used in the calibration process. The uncertainty recognized for this process results from: the realization of the ice point; the uncertainty in the calibration of the SPRT; and the temperature fluctuations in the calibration baths. All other sources of error are considered negligible.

The uncertainty in the realization of the ice point was determined by examining years of data accumulated from measuring the ice point on the SPRT before a triple point of water cell was used. The spread was found to be 0.005 °C.

The expanded uncertainty in the calibration of the SPRT is given in NIST Internal Report 5319, "Assessment of Uncertainties of Calibration of Resistance Thermometers at the National Institute of

Standards and Technology", [5] as approximately 0.00006 °C at the triple point of water, 0.001 °C in the range of 0 to 661 °C and 0.0004 °C in the range of -189.34 to 0.01 °C. In this paper, the value of 0.001 °C will be used throughout the entire range as the uncertainty of the SPRT.

The temperature fluctuations in the calibration baths were determined by simultaneous measurements using two or three SPRTs placed at various depths and at different locations in the baths. These measurements were made at several temperatures throughout the range of each calibration bath. The values chosen for the standard uncertainty due to radial and horizontal bath temperature fluctuations were the maximum differences between the SPRT readings divided by 2. Normally, for rectangular distribution, one would estimate the standard uncertainty by dividing by the $\sqrt{3}$ instead of 2. Although we have not seen fluctuations larger then indicated by these values, it is possible that they may occasionally be larger; consequently, we use the larger uncertainty. They are shown in Table 4. The square root of the sum-of-the squares of each component was calculated to give the Type B Standard Uncertainty (u_j). Twice the Type B standard uncertainty in each temperature range ($2u_j$) is given in Table 4.

TABLE 4

TYPE B EVALUATION OF STANDARD UNCERTAINTY

Temperature Range (°C)	Ice Point*	Platinum Resistance Thermometer	Bath Temperature Fluctuations	Twice the Type B Standard Uncertainty ($2u_j$)
-100 to 0	+0/-0.005	0.001	±0.005	0.014
0 to 50	+0/-0.005	0.001	±0.005	0.014
50 to 100	+0/-0.005	0.001	±0.005	0.014
0 to 100	+0/-0.005	0.001	±0.005	0.014
100 to 200	+0/-0.005	0.001	±0.005	0.014
200 to 300	+0/-0.005	0.001	±0.005	0.014
300 to 500	+0/-0.005	0.001	±0.005	0.014

*The numbers listed at the ice point represent the maximum deviation of 0.005 °C from the ice point (0 °C).

3.3. Calculation of the Combined Standard Uncertainty and the Expanded Uncertainty

The expanded uncertainty, i.e., the combined standard uncertainty (u_c) multiplied by the coverage factor k=2, for the liquid-in-glass thermometers is given in Table 5. These values are the square root of the sum of the squares of the Type A (u_i) and Type B (u_j) standard uncertainties given in Tables 3 and 4.

TABLE 5

EXPANDED UNCERTAINTIES FOR LIQUID-IN-GLASS THERMOMETERS

Temperature Range (°F)	Thermometer Graduation (°F)	Twice the Type A Standard Uncertainty ($2u_i$)	Twice the Type B Standard Uncertainty ($2u_j$)	Expanded Uncertainty ($2u_c$)
-60 to -30	0.2	0.036	0.025*	0.044

Temperature Range (°C)	Thermometer Graduation (°C)	Twice the Type A Standard Uncertainty ($2u_i$)	Twice the Type B Standard Uncertainty ($2u_j$)	Expanded Uncertainty ($2u_c$)
0 to 50	0.1	0.011	0.014	0.018
50 to 100	0.1	0.015	0.014	0.021
0 to 100	0.2	0.019	0.014	0.024
100 to 200	0.2	0.056	0.014	0.058
200 to 300	0.5	0.050	0.014	0.052
300 to 500	1.0	0.160	0.014	0.161

*Fahrenheit equivalent of calculated value.

4. Tables Listing "Estimated" Uncertainties of Liquid-in-Glass Thermometers

Since expanded uncertainties could be obtained only for a limited class of thermometers that were used as check standard thermometers, estimations of uncertainties were developed for the varied class of thermometers that are calibrated at NIST at

infrequent intervals. Tables 6 through 11 list tolerances and the "estimated" uncertainties for the various types of liquid-in-glass thermometers and, where data are available, expanded uncertainties are noted. The values listed vary for different temperature ranges, graduation intervals, and types of thermometers. The tables are essentially the same as those in NIST SP 250-23 [3]. A double asterisk appears where new estimates of uncertainties have been inserted.

"Estimated" uncertainty values given for thermometers where no recent data were available to determine the Type A standard uncertainty are the ones that were first published in Bureau of Standards Circular No. 8, August 11, 1921 [6]. The scale tolerances were chosen to be indicative of good manufacturing practice and represents the assumed accuracy of an uncalibrated liquid-in-glass thermometer. When a thermometer is manufactured, small errors in pointing (marks placed on a blank thermometer at various temperatures to be used as guides for the placement of the graduation lines) and graduating are inevitable. The tolerances must be sufficiently restrictive to ensure a satisfactorily high-grade thermometer, and at the same time not cause undue manufacturing difficulties.

In Table 12, "Estimated" Uncertainties for Beckmann and Calorimetric Thermometers, the estimated accuracy attainable in the measurement of any interval within the limits of the scale is given under the heading "Estimated uncertainty of interval". The values given are from Bureau of Standards Circular No. 8, October 14, 1926 [7]. No tolerances for scale error are given, although it is desirable that it be no larger than 0.02 °C over a 1.0 °C interval.

5. Future Plans

After examining the tables of uncertainties, it is obvious that more data are required on various types of liquid-in-glass thermometers to determine the uncertainty as defined in the CIPM Guide [2] and required by TN 1297 [1]. A large group of liquid-in-glass thermometers is currently being calibrated repeatedly to obtain data which will be used for these determinations. These data are being taken in the new calibration baths and they may result in a smaller value for the uncertainty. It will take approximately 18 months to complete this task. At that time, new uncertainty values will be computed and published in a revised version of SP 250-23.

TABLE 6

TOLERANCES AND "ESTIMATED"* UNCERTAINTIES FOR LOW-TEMPERATURE TOTAL-IMMERSION THERMOMETERS

Celsius scale graduated thermometers

Temperature range in °C	Type of thermometer	Graduation interval in °C	Tolerance in °C	"Estimated"* uncertainty in °C
-35 to 0	Mercury	1.0 or 0.5	0.5	0.1 to 0.2
-35 to 0	Mercury	0.2	0.4	0.02 to 0.05
-56 to 0	Mercury-thallium	0.5	0.5	0.1 to 0.2
-56 to 0	Mercury-thallium	0.2	0.4	0.02 to 0.05
-200 to 0	Organic liquid	1.0	2.0	0.2 to 0.5

Fahrenheit scale graduated thermometers

Temperature range in °F	Type of thermometer	Graduation interval in °F	Tolerance in °F	"Estimated"* uncertainty in °F
-35 to 32	Mercury	1.0 or 0.5	1.0	0.1 to 0.2
-35 to 32	Mercury	0.2	0.5	0.04**
-69 to 32	Mercury-thallium	1.0 or 0.5	1.0	0.1 to 0.2
-69 to 32	Mercury-thallium	0.2	0.5	0.04**
-328 to 32	Organic liquid	2.0 or 1.0	3.0	0.3 to 0.5

* Except where indicated otherwise, these values are from Ref. 6, Testing of Thermometers, BS Circular No. 8, 3rd Edition (August 11, 1921). Data are being taken at this time and new values will appear in a revised version of SP 250-23. The new values will probably be smaller, based on the data we have now.

** From calculated results given in Table 5.

TABLE 7

TOLERANCES AND "ESTIMATED"* UNCERTAINTIES FOR LOW-TEMPERATURE PARTIAL-IMMERSION THERMOMETERS

Celsius scale graduated thermometers

Temperature range in °C	Type of thermometer	Graduation interval in °C	Tolerance in °C	"Estimated"* uncertainty in °C
-35 to 0	Mercury	1.0 or 0.5	0.5	0.2 to 0.3
-56 to 0	Mercury-thallium	1.0 or 0.5	0.5	0.2 to 0.3
-90 to 0	Organic liquid	1.0	3.0	0.4 to 1.0

Fahrenheit scale graduated thermometers

Temperature range in °F	Type of thermometer	Graduation interval in °F	Tolerance in °F	"Estimated"* uncertainty in °F
-35 to 32	Mercury	1.0 or 0.5	1.0	0.3 to 0.5
-69 to 32	Mercury-thallium	1.0 or 0.5	1.0	0.3 to 0.5
-130 to 32	Organic liquid	2.0 or 1.0	5.0	0.8 to 2.0

* These values are from Ref. 6, Testing of Thermometers, BS Circular No. 8, 3rd Edition (August 11, 1921). Data are being taken at this time and new values will appear in a revised version of SP 250-23. The new values will probably be smaller, based on the data we have now.

TABLE 8

TOLERANCES AND "ESTIMATED"* UNCERTAINTIES FOR CELSIUS TOTAL-IMMERSION MERCURY THERMOMETERS

Temperature range in °C	Graduation interval in °C	Tolerance in °C	"Estimated"* uncertainty in °C
Thermometers graduated below 150 °C			
0 up to 150	1.0 or 0.5	0.5	0.1 to 0.2
0 up to 150	0.2	0.4	0.02**
0 up to 100	0.1	0.3	0.02**
Thermometers graduated below 300 °C			
0 up to 100	1.0 or 0.5	0.5	0.05**
Above 100 up to 300		1.0	0.05**
0 up to 100	0.2	0.4	0.02**
Above 100 up to 200		0.5	0.06**
Thermometers graduated above 300 °C			
0 up to 300	2.0	2.0	0.2 to 0.5
Above 300 up to 500		4.0	0.5 to 1.0
0 up to 300	1.0 or 0.5	2.0	0.16**
Above 300 up to 500		4.0	0.16**

* Except where indicated otherwise, these values are from Ref. 6, Testing of Thermometers, BS Circular No. 8, 3rd Edition (August 11, 1921). Data are being taken at this time and new values will appear in a revised version of SP 250-23. The new values will probably be smaller, based on the data we have now.

** From calculated results given in Table 5.

TABLE 9

TOLERANCES AND "ESTIMATED"* UNCERTAINTIES FOR FAHRENHEIT TOTAL-IMMERSION MERCURY THERMOMETERS

Temperature range in °F	Graduation interval in °F	Tolerance in °F	"Estimated"* uncertainty in °F
Thermometers graduated below 300 °F			
32 up to 300	2.0	1.0	0.2 to 0.5
32 up to 300	1.0 or 0.5	1.0	0.1 to 0.2
32 up to 212	0.2 or 0.1	0.5	0.02 to 0.05
Thermometers graduated below 600 °F			
32 up to 212	2.0 or 1.0	1.0	0.2 to 0.5
Above 212 up to 600		2.0	0.5
Thermometers graduated above 600 °F			
32 up to 600	5.0	4.0	0.5 to 1.0
Above 600 up to 950		7.0	1.0 to 2.0
32 up to 600	2.0 or 1.0	3.0	0.2 to 1.0
Above 600 up to 950		6.0	0.5 to 1.0

* These values are from Ref. 6, Testing of Thermometers, BS Circular No. 8, 3rd Edition (August 11, 1921). Data are being taken at this time and new values will appear in a revised version of SP 250-23. The new values will probably be smaller, based on the data we have now.

TABLE 10

TOLERANCES AND "ESTIMATED"* UNCERTAINTIES FOR
CELSIUS PARTIAL-IMMERSION
MERCURY THERMOMETERS

Temperature range in °C	Graduation interval in °C[a]	Tolerance in °C	"Estimated"* uncertainty in °C[b]
Thermometers graduated below 150 °C			
0 up to 100	1.0 or 0.5	1.0	0.1 to 0.3
0 up to 150	1.0 or 0.5	1.0	0.1 to 0.5
Thermometers graduated below 300 °C			
0 up to 100	1.0	1.0	0.1 to 0.3
Above 100 up to 300		1.5	0.5 to 1.0
Thermometers graduated above 300 °C			
0 up to 300	2.0 or 1.0	2.5	0.5 to 1.0
Above 300 up to 500		5.0	1.0 to 2.0

* These values are from Ref. 6, Testing of Thermometers, BS Circular No. 8, 3rd Edition (August 11, 1921). Data are being taken at this time and new values will appear in a revised version of SP 250-23. The new values will probably be smaller, based on the data we have now.

[a]Partial-immersion thermometers are sometimes graduated in smaller intervals than shown in these tables, but this in no way improves the performance of the thermometers, and the listed tolerances and uncertainties still apply.

[b]The uncertainties shown are attainable only if emergent-stem temperatures are approximately known and corrections made.

TABLE 11

TOLERANCES AND "ESTIMATED"* UNCERTAINTIES FOR FAHRENHEIT PARTIAL-IMMERSION MERCURY THERMOMETERS

Temperature range in °F	Graduation interval in °F[a]	Tolerance in °F	"Estimated"* uncertainty in °F[b]
Thermometers graduated below 300 °F			
32 up to 212	2.0 or 1.0	2.0	0.2 to 0.5
32 up to 300	2.0 or 1.0	2.0	0.2 to 1.0
Thermometers graduated below 600 °F			
32 up to 212 Above 212 up to 600	2.0 or 1.0	2.0 3.0	0.2 to 0.5 1.0 to 2.0
Thermometers graduated above 600 °F			
32 up to 600 Above 600 up to 950	5.0 or 2.0	5.0 10.0	1.0 to 2.0 2.0 to 3.0

* These values are from Ref. 6, Testing of Thermometers, BS Circular No. 8, 3rd Edition (August 11, 1921). Data are being taken at this time and new values will appear in a revised version of SP 250-23. The new values will probably be smaller, based on the data we have now.

[a]Partial-immersion thermometers are sometimes graduated in smaller intervals than shown in these tables, but this in no way improves the performance of the thermometers, and the listed tolerances and uncertainties still apply.

[b]The uncertainties shown are attainable only if emergent-stem temperatures are approximately known and corrections made.

TABLE 12

"ESTIMATED"* UNCERTAINTIES FOR BECKMANN AND CALORIMETRIC THERMOMETERS

Type of thermometer	Graduation interval	Maximum desirable difference in correction	"Estimated"* Uncertainty of interval
Beckmann	0.01 °C	0.01 °C over 0.5 °C interval for setting of 20 °C	0.002 to 0.005 °C
Bomb calorimetric	0.01 °C	0.02 °C over 1.5 °C interval	0.005 to 0.01 °C
Bomb calorimetric	0.02 °C	0.02 °C over 1.5 °C interval	0.005 to 0.01 °C
Bomb calorimetric	0.05 °F	0.04 °F over 2.5 °F interval	0.01 to 0.02 °F
Gas calorimetric	0.1 °F	0.15 °F over a 5 °F interval	0.02 to 0.05 °F

* These values are from Ref. 7, Testing of Thermometers, BS Circular No. 8, 4th Edition (October 14, 1926).

6. References

[1] Taylor, Barry N., and Kuyatt, Chris E., Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, NIST Technical Note 1297 (January 1993).

[2] Guide to the Expression of Uncertainty in Measurement. Geneve, Switzerland: International Organization for Standardization; October 1993. 101 p.

[3] Wise, Jacquelyn, Liquid-in-Glass Thermometer Calibration Service, NIST Special Publication 250-23 (September 1988).

[4] "The International Temperature Scale of 1990," Metrologia 27, No. 1, 3-10 (1990); Metrologia 27, 107 (1990).

[5] Strouse, G. F., and Tew, W. L., "Assessment of Uncertainties of Calibration of Resistance Thermometers at the National Institute of Standards and Technology," NIST Internal Report 5319, 16 pp., (1993).

[6] Testing of Thermometers, Bureau of Standards Circular No. 8, 3rd edition, (August 11, 1921).

[7] Testing of Thermometers, Bureau of Standards Circular No. 8, 4th edition, (October 14, 1926).